

# Investigating Impacts of Climate Change on the Weser Estuary

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## Summary

According to the Intergovernmental Panel on Climate Change, global climate change will have profound impact on our environment. This applies to estuaries in particular, as they are not only influenced by changes in the meteorological conditions, but also by the mean sea level rise, changes in river runoff regimes and possibly more intense storm surges. As this makes impact studies in estuaries rely on impact studies of neighboring systems such as watersheds or adjacent shelf seas, uncertainties may accumulate. This complicates to derive reliable projections for planners and decision makers. This contribution describes a work package of a joint climate impact project of the German state Lower Saxony. The aim of the project is to investigate impacts on hydrodynamics and salinities of the Weser estuary. The impact model used in the study is a 3D hydrodynamic modelling tool. The article focuses among others on results and discussion of a mean sea level rise scenario.

## Keywords

hydrodynamic modelling, climate impact, Weser estuary, salinity intrusion, tidal dynamics

## Zusammenfassung

*Dem Intergovernmental Panel on Climate Change zufolge wird der globale Klimawandel in der Zukunft weitreichende Folgen für unsere Lebensumwelt haben. Dies gilt insbesondere für Küstenbereiche wie Ästuarare, da sie nicht nur durch meteorologische Änderungen, sondern auch durch den Anstieg des mittleren Meeresspiegels, Änderungen im Abflussregime und möglicherweise auch durch verstärkte Sturmfluten gefährdet sind. Da Impactuntersuchungen in Ästuaren demnach von Impactstudien in benachbarten Systemen wie beispielsweise der Einzugsgebiete oder angrenzender Meeresgebiete abhängen, addieren sich Unsicherheiten. Dies erschwert die Ableitung von belastbaren Projektionen für politische Entscheidungsträger und Planer. Dieser Beitrag beschreibt ein Teilprojekt des Klimafolgenforschungsprojektes KLIFF des Landes Niedersachsen, welches sich mit den Folgen für die Hydrodynamik und die Salzgehalte im Weserästuar befasst. Als Impactmodell kommt ein 3D hydrodynamisch-numerisches Modell zum Einsatz. Schwerpunkt des Beitrags sind unter anderem Ergebnisse und Diskussion eines Szenarios mit einem mittleren Meeresspiegelanstieg.*

## Schlagwörter

*Hydrodynamische Modellierung, Klimafolgen, Weserästuar, Salzintrusion, Tidedynamik*

**Contents**

1 Introduction ..... 542  
 2 Salinity and hydrodynamics of the Weser Estuary in its present state ..... 543  
 3 Methods ..... 544  
   3.1 Modelling tool ..... 544  
   3.2 Weser estuary model ..... 545  
   3.3 Computation of investigated tidal characteristics ..... 545  
 4 Investigation of a mean sea level rise scenario ..... 546  
   4.1 Experimental design ..... 546  
   4.2 Investigated scenario ..... 547  
   4.3 Results ..... 547  
 5 Summary and discussion ..... 548  
 6 References ..... 550

**1 Introduction**

The salinity distribution and the hydrodynamics of the Weser estuary are influenced by the tides in the German Bight, the runoff from the watershed, meteorological influences such as wind- or storm events and the geometry of the estuary. Climate change may impact the Weser directly by change of the meteorological forcing but mainly indirectly by changes in neighboring systems like the North Sea or the watershed, which provide important boundary conditions of the estuary (see Fig. 1).

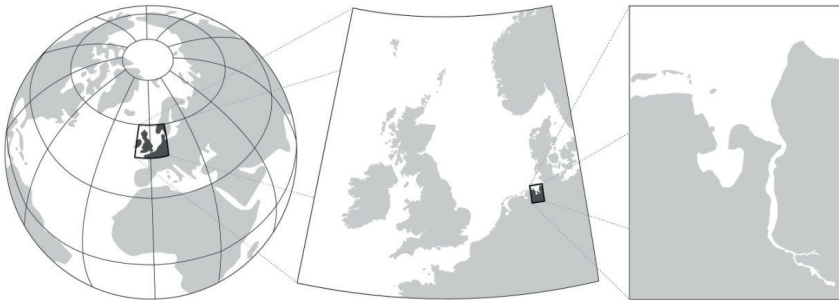


Figure 1: Global climate changes impact the Weser estuary mostly by changes of other systems like the North Sea, which poses a challenge to climate impact research.

Research has been undertaken in the last decades by the German state Lower Saxony (projects KLIMU and KRIM, e.g. SCHIRMER and SCHUCHARDT 2001) and currently by the Federal Ministry of Transport, Building and Urban Affairs (KLIWAS, see SEIFFERT et al., this volume) to investigate possible impacts of climate change on the Weser. Yet there is still uncertainty on both the side of the changed forcing as well as on the side of the system’s response. Coastal planners and decision makers however are in need of reliable projections, as adaptation measures need to be envisaged well in advance in order to be prepared for the challenges ahead. This has motivated the Ministry for Science and

Culture of Lower Saxony to investigate impacts of climate change on the Weser estuary as part of yet another interdisciplinary research program launched in 2009 (KLIFF – [www.kliff-niedersachsen.de](http://www.kliff-niedersachsen.de)).

To investigate changes of the salinity distribution and hydrodynamics of the estuary, a 3D model was built up and validated with observations of past events. With help of scenario simulations, possible impacts of climate change on today's state of the Weser estuary with its natural seasonal, periodic and meteorologically induced variations were investigated. To achieve more reliable projections, the attempt was made to decrease or at least quantify the uncertainty of the projections induced by internal variability of the system and the boundary condition uncertainty.

The study was carried out in strong collaboration with partners investigating climate change impact on the adjacent watersheds of the estuary (e.g. KREYE et al. 2010) and the groundwater (e.g. YANG et al. 2013).

In this contribution, an introduction on the hydrodynamics and salinity intrusion of the Weser estuary in its current state is provided in Section 2. Methods are described in Section 3. The main part of this contribution focuses on results of a simple mean sea level rise scenario which is described in Section 4, followed by a summary and discussion in Section 5.

## 2 Salinity and hydrodynamics of the Weser Estuary in its present state

A detailed study of the hydrodynamics of the Weser Estuary in the present state was carried out within this study. Here, a short summary is presented. In today's state, the tidal range of the estuary amounts to approximately 2.8 m in the outer estuary (Leuchtturm Alte Weser) and then continuously increases upstream toward a maximum of 4.10 m at the weir in Bremen. The tidal dynamics of the estuary are influenced by astronomical periodic variations such as the spring-neap cycle. Further upstream, they are also influenced by the runoff. The runoff however, inflowing at the weir from the Mittelweser and also from smaller adjacent catchments, underlies strong seasonal variations. The long-term mean amounts to approximately  $324 \text{ m}^3 \text{ s}^{-1}$  (1990-2010). The lowest monthly means occur in September, the highest in March ( $166 \text{ m}^3 \text{ s}^{-1}$  and  $564 \text{ m}^3 \text{ s}^{-1}$ , extremes of  $74 \text{ m}^3 \text{ s}^{-1}$  and  $2190 \text{ m}^3 \text{ s}^{-1}$ , respectively).

The position of the mixing zone between freshwater and seawater varies in relation of those values. It can be described by the distance of the tidally averaged 2- and 10 psu isohalines from the tidal weir in Bremen ( $P_{12}$ ,  $P_{110}$ ). During average runoff conditions, which occur in spring or autumn after or before the increased winter high water, the 2 psu isohaline is found at a distance of approximately 57 km from the tidal weir as can be seen in Fig. 2 ( $P_{12} = 57 \text{ km}$ ,  $P_{110} = 70 \text{ km}$ ). In the summer when runoff is typically very low, it intrudes further upstream the estuary so that  $P_{12} = 52 \text{ km}$  for  $Q = 200 \text{ m}^3 \text{ s}^{-1}$ . During the high waters occurring in winter, a displacement downstream can be observed (e.g.  $P_{12} = 73 \text{ km}$  for  $Q = 1800 \text{ m}^3 \text{ s}^{-1}$ ).

An important indicator for sediment dynamics and the position of the estuarine turbidity maximum is the residual current velocity, which is shown in Fig. 2 (bottom) for average runoff conditions. In the upstream river reach up to a distance of approximately 57 km from the tidal weir, the vertical structure of the residual flow is mostly uniform. Downstream from here however, the bottom residual current velocity turns and becomes

landwards directed. In parallel to the position of the mixing zone, this null point of bottom residual current velocity is displaced down- or upstream with varying runoff.

The local variations of the salinity due to the tides are close to zero at seaward and the upstream ends of the mixing zone and increase toward the centre of the mixing one up to values of 12 psu. Simulations show that the vertical stratification also varies with runoff and the tides. During higher runoff and increasingly in neap conditions, stratification establishes with higher salinity in the lower and reduced salinity in the upper water column. This is observed especially during ebb current and has been described in literature as strain induced periodic stratification (SIMPSON et al. 1990).

In a prior publication of the authors, the impact of storms on salinity intrusion was investigated (ZORNDT et al. 2012). The investigation was based on past storm events and scenario storms which were extracted from North Sea model runs of project partners (GASLIKOVA et al. 2012). The simulations showed that depending on duration and intensity of the storm surge, a storm event can move the mixing zone up to 30 km further upstream.

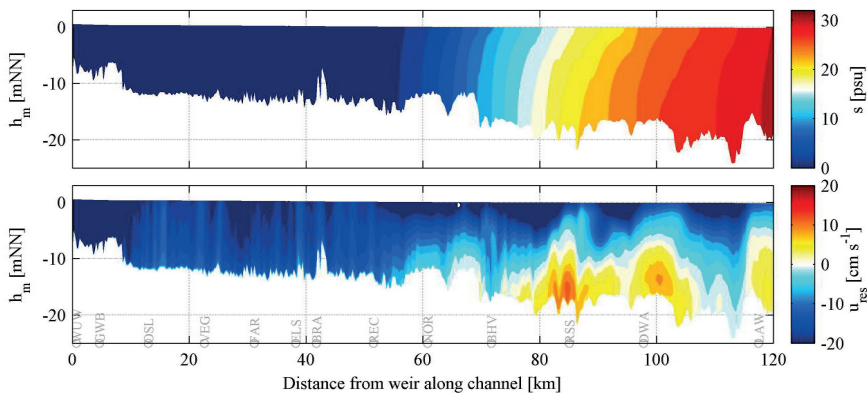


Figure 2: Salinity (top) and residual current velocity (bottom) along the river kilometre line, averaged over a spring-neap cycle of a simulation during average runoff conditions (MQ, see Section 4.1). Seawards directed current is defined to be negative (blue) landwards positive (red).

### 3 Methods

#### 3.1 Modelling tool

The modelling tool employed in this project has been developed by ZHANG and BAPTISTA (2008). It solves the Reynolds averaged Navier-Stokes equations with shallow water assumption and Boussinesq approximation. SELFE is a semi-implicit Eulerian-Lagrangian finite-element model based on a Galerkin finite element framework with linear shape functions for elevation. Terrain-following hybrid vertical coordinates are used. For turbulence closure, several one- or two equation models can be chosen. Being an open-source community tool, it provides several additional modules for studying among others tsunami inundation, sediment transport, oil spill or water quality. The modelling system is parallelized using domain decomposition. For a more comprehensive description, see ZHANG and BAPTISTA (2008).

### 3.2 Weser estuary model

The computational domain encompasses an area of 2,140 km<sup>2</sup> and contains 191,111 vertices and 372,708 elements. In the North, it stretches out to a latitude of approx. 54°. The domain boundaries follow the main dike protection lines and ends in the South at the tidal weir (see Fig. 1, right). The model partly incorporates tributaries mouting into the estuary. The river Hunte is modeled up to the city of Oldenburg and the smaller tributaries Hamme and Wümme reach up to Ritterhude and Niederbrockland, respectively.

To construct the bathymetry, data sets from multi- and single beam soundings as well as airborne data and a digital land model of Lower Saxony were used, which were provided by agencies of the Waterways and Shipping Administration of the German Federal Government and the land of Lower Saxony. The majority of data stems from surveys between 2006 and 2010. Thus, this period has been defined as the model's reference state.

The model is forced by water surface elevation at the Northern open boundary to the German Bight, freshwater input at the open boundaries of Ritterhude, Niederbrockland, Hunte, Ochtum, Geeste and Bremen as well as wind forcing over the wind. The model was calibrated based on a period in April 2009 characterized by medium runoff. It was validated by simulation of periods with varying runoff. In Fig. 3, a comparison between observed and simulated time series is presented for a validation period from winter 2003, in which a peak runoff value of 2190 m<sup>3</sup> s<sup>-1</sup> was observed.

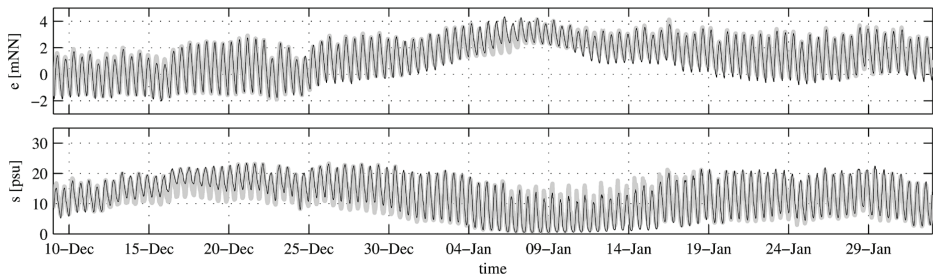


Figure 3: Observed (gray) and simulated (black) time series of elevation at the weir (top) and salinity at a station 85 km from the weir (bottom) for a validation period.

The skill of Murphy (1988) and the root mean squared error were used to quantitatively evaluate the model's ability of reproducing measured water surface elevation, current velocity and salinity. Average skill values amount to 0.95 for water surface elevation, 0.89 for salinity and 0.80 for current velocity, based on two validation periods and with 12 evaluated stations each, which partly consisted of up to three measuring devices distributed over the water column.

### 3.3 Computation of investigated tidal characteristics

The results presented in this contribution were derived with the following automated steps: The extracted simulated time series of 30 min. resolution were upscaled to 10 min. with spline interpolation. Salinity and current velocity time series were depth averaged for

most of the results presented here. Current velocity vectors were rotated into the main channel direction and only the main current direction was further evaluated, flood current defined as positive. Time series were split up into single tides. Beginning and end of each tide were defined to be low water for water surface elevation, lowest salinity for salinity and slack point after ebb for main current velocity. Tidal characteristics (TC) were calculated for each tide. Presented here are tidally averaged water level (MW), high water (HW), low water (LW), tidal range (TR), tidally averaged salinity ( $S_M$ ), tidal salinity maximum ( $S_{MAX}$ ) and residual of the current velocity in main channel direction ( $U_{RES}$ ). The tides between reference and scenario runs were matched and differences between the tidal characteristics ( $\Delta TC$ ) were computed for each tide.

## 4 Investigation of a mean sea level rise scenario

### 4.1 Experimental design

As mentioned in the introduction, attention was paid to decrease the uncertainty of the projections induced by internal variability of the system. In climate impact studies investigating the impact of changes in meteorological conditions directly (e.g. wind on storm surges as in GASLIKOVA et al. 2012), this can be solved by simulation of data from global climate model runs with varying initial conditions.

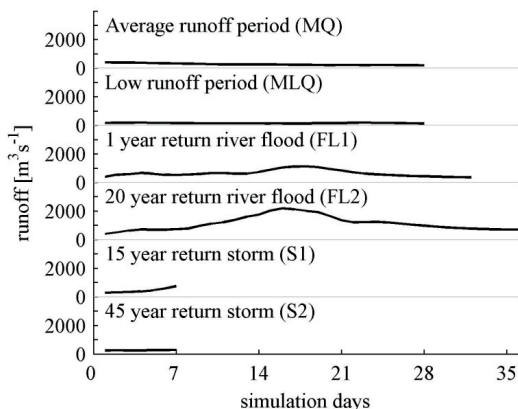


Figure 4: Representation of the reference state.

In this impact study however, the most dominant cause for change is not the impact of the meteorological forcing directly, but changes in boundary conditions from other systems such as the North Sea or the watershed. Due to limited information on the transient changes of the boundary conditions and limited numerical capacity, the impact simulations of this study are limited to shorter time periods. When this is the case, the simulated time slices should be chosen in a way to best capture the whole variability of the present state. In this respect, this study adapts the approach of projects like KRIM or KLIMU (e.g. GRABEMANN et al., 2001) and tests the investigated scenarios on a set of simulations each representing different characteristic situations in the reference state. The simulations are based on past events with boundary conditions generated from

measurements. The choice of simulations is based on the analysis of the present state (see Section 2). In total, six periods were chosen which represent typical periods of average runoff (MQ), low runoff (MLQ) and river floods with return values of approximately one and 20 years as well as storm surges (Fig. 4). This contribution however focuses only on results derived from the first four periods.

## 4.2 Investigated scenario

This contribution focuses solely on the results of a simple mean sea level rise (MSLR) scenario, which is considered a “likely” scenario. The investigated MSLR is 0.74 m which is based on the 5<sup>th</sup> assessment report of the Intergovernmental Panel on Climate Change (IPCC) and is there presented as the “most likely” value for global rise in 2100, assuming the representative concentration pathway RCP8.5 (IPCC 2013). In addition to this, a high end scenario was tested in this project which is not shown here. The MSLR is added to the time series for water surface elevation at the open North Sea boundary as a constant. This simplified approach is further discussed in Section 5. Neither taken into account in the results presented here are salinity changes at the open boundaries. Gradual changes of bathymetric and bottom roughness due to altered sedimentation patterns in the domain itself or changed roughness are to be expected, but not considered in the results presented here.

## 4.3 Results

The simulations of the reference state (see Section 4.1) were repeated with boundary conditions adapted to the investigated scenario (see Sec 4.2). Box- and whisker plots of the computed  $\Delta TC$  (see Section 3.3) are presented in Fig. 5 and 6. This contribution only presents results for three focus regions in the study region. The focus region BHV is located just north of the entrance to the narrow Unterweser reach of the estuary at Bremerhaven approximately 75 km from the tidal weir. It is characterized by a highly variable salinity depending on the tidal phase and the runoff. The focus region BRA is located at the latitude of the city of Brake in the inner estuary (45 km distance from weir) and is at today’s beginning of the brackish water zone, meaning that salinities are mostly below 1 psu except for summer and autumn when they can hit peaks of 5 psu during high tide. The focus region HB is located in the tidal freshwater reach about 15 km from the weir.

The results presented in Fig. 5 illustrate that the investigated scenario of 0.74 m of MSLR at the open boundary leads to a change in tidal dynamics. In the upstream part of the inner estuary, an increase of the M2 and M4 tidal constituent amplitudes (not shown here) leads to increase of tidal range TR. In focus region HB, this increase amounts to approximately 15 cm (Fig. 5d). The increase in TR goes along with a decrease of the tidal low water LW relative to the imposed MSLR (Fig. 5c). The tidal high water (Fig. 5b) is less affected and the roughly corresponds to the imposed MSLR. The increase in mean water level (Fig. 5a) is lower than the imposed MSLR, which is again more pronounced upstream the estuary. All in all, the computed  $\Delta TC$ s are similar for the four representations of the reference state MQ, MLQ, FL1 and FL2.

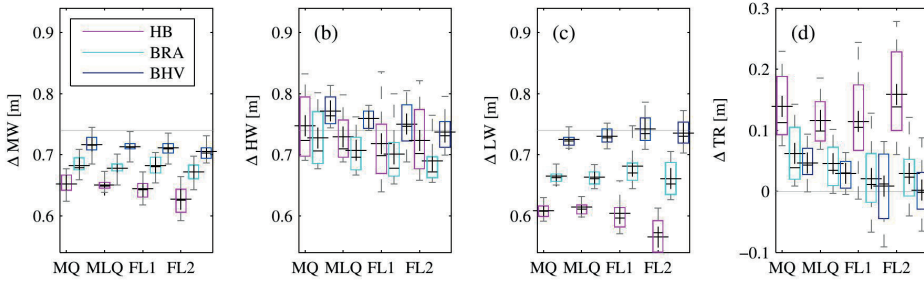


Figure 5: Computed differences  $\Delta TC$  for water surface elevation between the MSL 0.74 m scenario- and the reference simulations for three focus areas. The boxes and whiskers indicate 25/75 % and 10/90 % percentiles, respectively, medians are shown as (-), means as (+).

The salinity is also affected by the scenario which is shown in Fig. 6. Generally, the mixing zone between salt and fresh water (see Fig. 2) intrudes further upstream the estuary (not shown here, see for example SEIFFERT et al., this volume). This leads to an increase of salinity upstream the estuary. The average salinity  $S_M$  increases by approx. 2 psu in focus region BHV (Fig. 6a). This applies to the simulations of average and low runoff and also to periods of river floods. In the focus region BRA, only a very small increase of  $S_M$  can be observed, but the tidal maximum salinity  $S_{MAX}$  increases by almost 1 psu during the MNQ simulation (Fig. 6b). This shows that especially during low runoff conditions in summer, increased salinity may be a problem for use of estuarine water in this region.

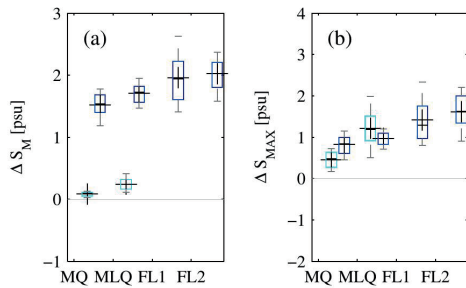


Figure 6: Continued from Figure 5 for salinity.

The changes in tidal dynamics are accompanied by changes in the current velocities in main channel direction. The simulations reveal that the intensity of the flood current is strengthened in comparison with the ebb current velocities (not shown here).

### 5 Summary and discussion

The aim of the project presented here is to investigate impacts of climate change on hydrodynamics and salinities of the Weser estuary, Germany. A 3D hydrodynamic model of the estuary was built up and validated successfully. To describe the present state of the estuary and best capture internal natural variability, a set of simulations was chosen all representing different characteristic periods of the current state such as river floods, average and low runoff and storm surges. A simple scenario with a MSLR of 0.74 m was



simulated and characteristic values of the scenario simulations were compared to those of the reference simulations.

Results show that the overall rise in mean water level is accompanied with changes in the tidal dynamics. In particular, an increase in tidal range with a fall of the low water levels as well as an increase of flood in relation to ebb current can be observed. The salinity in the inner estuary increases. There is a general tendency towards an upstream displacement of the mixing zone and null point of bottom residual current velocity. The reason for the upstream displacement may be the intensification of flood current due to decrease of dissipation.

To put the results into perspective and derive meaningful information for practitioners and decision makers, it is crucial to shortly discuss the uncertainties of the investigated scenario and comment on the confidence of the results. According to the IPCC (2013) it is "virtually certain" that the rate of global mean sea level rise (GMSLR) has accelerated during the last centuries and future rise rates are „very likely“ to exceed those observed in the last years. Projections for the GMSLR until 2100 are presented for different representative concentration pathways (RCPs), all providing a likely range and an average. This project focuses on RCP8.5, assuming a continued rise in greenhouse gas emissions. From the range of likely GMSLR values given for this scenario, the most likely one is chosen. On the global scale, this value can be assigned a "medium confidence" for RCP8.5 (IPCC 2013), but it should be mentioned that the confidence decreases drastically when the GMSLR is projected directly to the boundary condition of the Weser due to two reasons: To begin with, there is evidence that the GMSLR will not be distributed evenly on the globe. However, adapting the global projection is not possible due to limited knowledge on these processes. Secondly, there is evidence that the tidal dynamics (TDs) in the North Sea will change which might lead to higher or lower tidal range in the German Bight. The impact of MSLR on the North Sea TDs has recently been investigated in some studies but the most reliable results are still provided by PLÜB (2004) due to better resolution of the Wadden Sea area. However, PELLING et al. (2013) have shown with a simplified experimental design that TD changes mainly depend on the energy dissipation induced by the flat Wadden Sea areas of the German Bight. This indicates that changes in sedimentation patterns and possibly coastline changes will play an important role for the future changes in TDs under a MSLR. Therefore, it can be argued that not deforming the tidal signal at the German Bight inherits the same amount of boundary condition uncertainty as deforming it without further investigating TD changes in the North Sea. Furthermore, as mentioned in Section 4.2, changes in sedimentation patterns can be expected to occur within the Weser just as they will within the North Sea. As bathymetry and roughness can be considered boundary conditions in this respect, this leads to further boundary condition uncertainty which will be investigated in further research within this project.

Despite these uncertainties in scenario and boundary conditions, the results derived from the scenario presented here can be seen as a best estimate at the time, assuming that greenhouse emissions do not decline. As mentioned earlier, the investigations will be complemented by a high end scenario and further investigations aiming for quantifying uncertainties induced by boundary conditions.

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